MultiSector Dynamics in Earth & Environmental Systems Modeling: *Exploring Cross-Scale Interfaces Among Human and Natural Systems*

Bob Vallario

Program Manager
MultiSector Dynamics in
Earth and Environmental Systems Modeling

ICEMM
March 18, 2020

U.S. DEPARTMENT OF ENERGY

Office of Science

Office of Biological and Environmental Research

MultiSector Dynamics (MSD) Goal

Explore the *complex interactions and potential co-evolutionary pathways* within the integrated human-Earth system, including natural, engineered, and socioeconomic systems and sectors.

Strategic Objectives

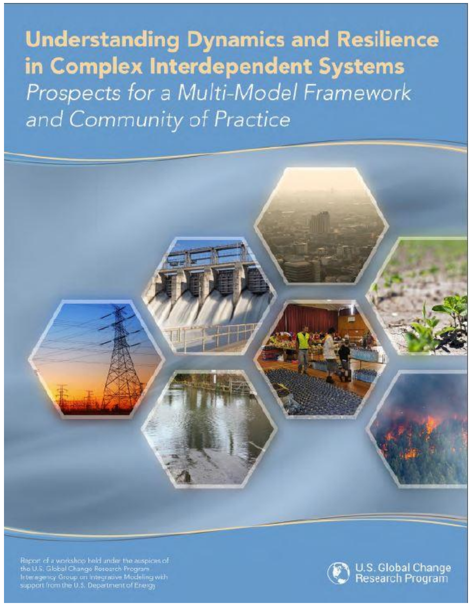
1. **Forces and Patterns.** Reveal the combination of factors, varying by geographies, that contribute most significantly to ***patterns of development in transregional, regional, and sub-regional landscape evolutions****,* including interactions and interdependencies among natural and built environments and human processes and systems.

2. **Stabilities and Instabilities.** Identify the characteristics of interacting natural and built environments and human processes that lead to ***stabilities* and *instabilities*** across systems, sectors, and scales, and deliver new insights into the role of strong interdependencies, feedbacks, and compounding influences and stressors.

3. **Foresight**. Explore how development patterns, stabilities, instabilities, and ***systems resilience*** may evolve within multisector, multi-scale landscapes as a result of ***<u>future</u> forces, stressors, and disturbances*****…** and reveal what pathways, characteristics, and risk profiles may emerge from ***both gradual and abrupt transitions***.

History

- Early 1990s-2009 – Early work in modeling of the contribution of anthropogenic and natural forcing in climate evolution…work in impacts on and responses by land systems with feedbacks…incorporation into model-driven scenarios of consistent land and technology development pathways.



https://www.globalchange.gov/sites/globalchange/files/Multi-Model_Framework_WorkshopReport_Dec_2016_Final.pdf

- 2009-2016 - a notable pivot with focus on effects and systems responses to climate and weather-related extremes (impacts, adaptations, vulnerabilities), motivated by a 2009 community workshop report.

- **2016-present** - a transformational shift toward more comprehensive MultiSector Dynamics, catalyzed by 2016 report on *dynamics and resilience in complex, adaptive systems*.

Funding Mechanisms for CESD…and for MSD

Laboratory Investments

- Science Focus Areas (~$1M-$22M)
- Large Projects
  - e.g., NGEE-A; NGEE-T; Ameriflux, IDEAS, ESGF, ESM SciDAC projects
- Small Projects (<1$M/year)
- Collaborators on University Projects
  - ($20K to >$1M)

University Investments

- Cooperative Agreements
  - Small ($100K) to Large ($4M)
- Large University projects
  - (~1M/year)
- Small University projects
  - (<$1M/year, PI-driven)
- Small Projects in response to SFAs
- Collaborators to Lab projects
  - Independently funding line or as sub-awards from Labs

National Lab SFAs/ and Projects and University Collaborative Agreements

1. Integrated Multi-sector, Multi-scale Modeling (IM3)
   SFA PI: Jennie Rice
2. Integrated Human Earth Systems Dynamics (IHESD)
   SFA PI: Mohamad Hejazi
3. Integrated Coastal Modeling (ICOM)*
   PI: Ian Kraucunas
4. Interdisciplinary Research for Arctic Coastal Environments (InteRFACE)*
   PI: Joel Rowland
5. Program on Coupled Human Earth Systems (PCHES)
   CA PI: John Weyant/Karen Fisher-Vanden/Rob Nicholas
6. Integrated Global Systems Modeling (IGSM)
   CA PI: Ron Prinn /John Reilly
7. HyperFACETS*
   CA PI: Paul Ullrich

* Collaborative program funding

Partners (examples):

Integrated Multi-sector, Multi-scale Modeling (IM3) SFA

Scope and Focus: Humans interactions with the local/regional environment

Mechanistic understanding and limits to predictability in the evolution of local to regional landscapes and the accompanying interactions and feedbacks among sectors, infrastructures, resources, and the natural environment. Exploring stressors, vulnerabilities, tipping points, resilience, and long term drivers for co-evolving systems. Builds from flexible and extensible modeling capabilities that capture the dynamic interactions among climate and weather extremes, energy, water, socioeconomic, and critical infrastructure systems and sectors, testing different leadership-class modeling components (for example from DOE and other agencies) in various model framework configurations. Develop insights on levels of complexity, multi-model coupling strategies, and spatial and temporal resolutions and their implications for simulation fidelity, propagation of uncertainties, and suitability for best-in-class modeling methods for specific science questions.

Principal Investigators:

Ian Kraucunas - Pacific Northwest National Laboratory
Jennie Rice (Interim) - Pacific Northwest National Laboratory

Collaborative Institutional Leads:

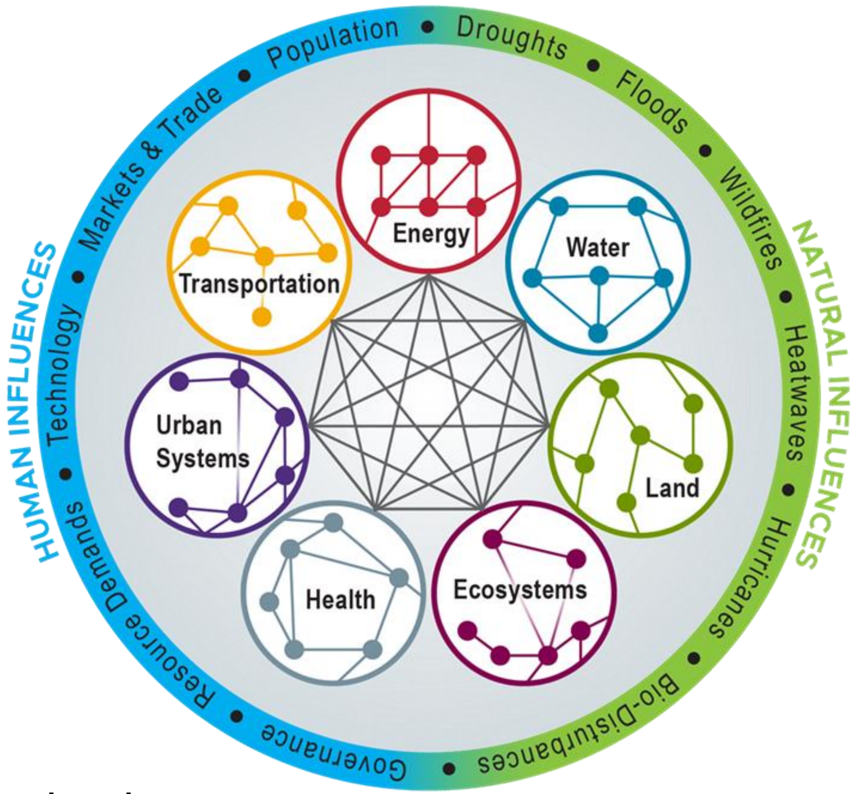
Melissa Allen-Dumas - Oak Ridge National Laboratory
Jared Carbone - Colorado School of Mines
Alejandro Flores - Boise State University
Andrew Jones - Lawrence Berkeley National Laboratory
Dan Li - Boston University
Hong-Yi Li - University of Houston
Jordan Macknick - National Renewable Energy Laboratory
Brian O'Neill - University of Denver
Patrick Reed - Cornell University
Vince Tidwell - Sandia National Laboratories
Ethan Yang - Lehigh University

Project Participants:

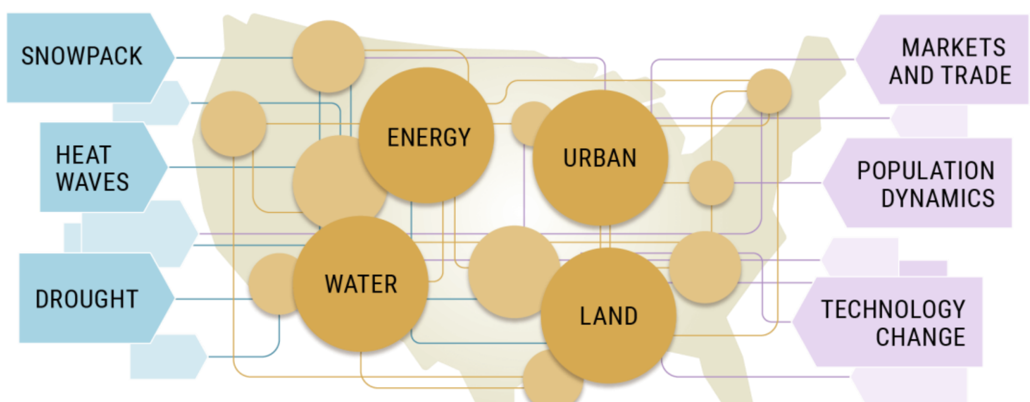
Christa Brelsford - Oak Ridge National Laboratory
Casey Burleyson - Pacific Northwest National Laboratory
Stuart Cohen - National Renewable Energy Laboratory
Maoyi Huang - Pacific Northwest National Laboratory
Gokul Iyer - Pacific Northwest National Laboratory
Tom Lowry - Sandia National Laboratories
Ryan McManamay - Oak Ridge National Laboratory
David Millard - Pacific Northwest National Laboratory
Z. Todd Taylor - Pacific Northwest National Laboratory
Chris Vernon - Pacific Northwest National Laboratory
Nathalie Voisin - Pacific Northwest National Laboratory

Website: https://im3.pnnl.gov/

Integrated Multi-sector, Multi-scale Modeling (IM3) SFA CONTD.



Past emphasis:



Illustrative Highlights –Landscape-Scale Processes and Dynamics with a Focus on Impacts, Responses, Resilience and Transformations in Coupled Human-Environmental Landscapes

- The Role of Climate Co-variability on Bioenergy Crop Yields in the Conterminous United States
- Improving Projections of Future Hydropower Changes in the Western U.S.
- The Many Shapes of Reservoirs
- Kernels of Knowledge: How Land Use Decisions Affect Crop Productivity
- Tethys Tackles Downscaling Challenge for Regional Water Withdrawals
- Reservoir Management Alters Flood Frequency at the Regional Scale
- Sensitivity of Western U.S. Power System Dynamics to Droughts Compounded with Fuel Price Variability
- CERF – A Geospatial Model for Assessing Future Electricity Expansion
- Accounting for Groundwater Use and Return Flow Improves Modeling of Water Management
- Evolution of Extreme Heat Risk in Cities: Interacting Implications of Climate, Population Dynamics, and Urban Heat Mitigation
- Quantifying Decision Uncertainty in Water Management via a Coupled Agent-Based Model
- Quantifying the Impacts of Heat Waves on Power Grid Operations
- The Nonlinear Response of Storm Surge to Sea-Level rise: A Modeling Approach

Integrated Human and Earth Systems Dynamics (IHESD) SFA

FOCUS: Humans interactions within the global Earth system

Exploring the role of human activities in Earth systems science with improved understanding of economic activity, resource utilization, broad-scale energy and land use trajectories, hydrology, biogeochemical cycles and feedbacks to the global Earth system. Built around leadership-class mid-complexity models (GCAM and the GCAM ecosystem of models) and process level understanding that can be incorporated into leadership class ESMs such as E3SM. Explores not only how humans directly influence Earth systems, but the iterative process of how climate variability and extreme events in turn interact with evolving human systems and alter long-term human system that can alter overall human-Earth system dynamics. A strong component of the work is to understand how uncertainty about economic decision-making and feedbacks propagate through the fully coupled human-Earth system, capitalizing on mid-level model complexity, the development and use of emulators, and computational tractability..

Principal Investigator:

Leon Clarke – Pacific Northwest National Laboratory (PNNL)

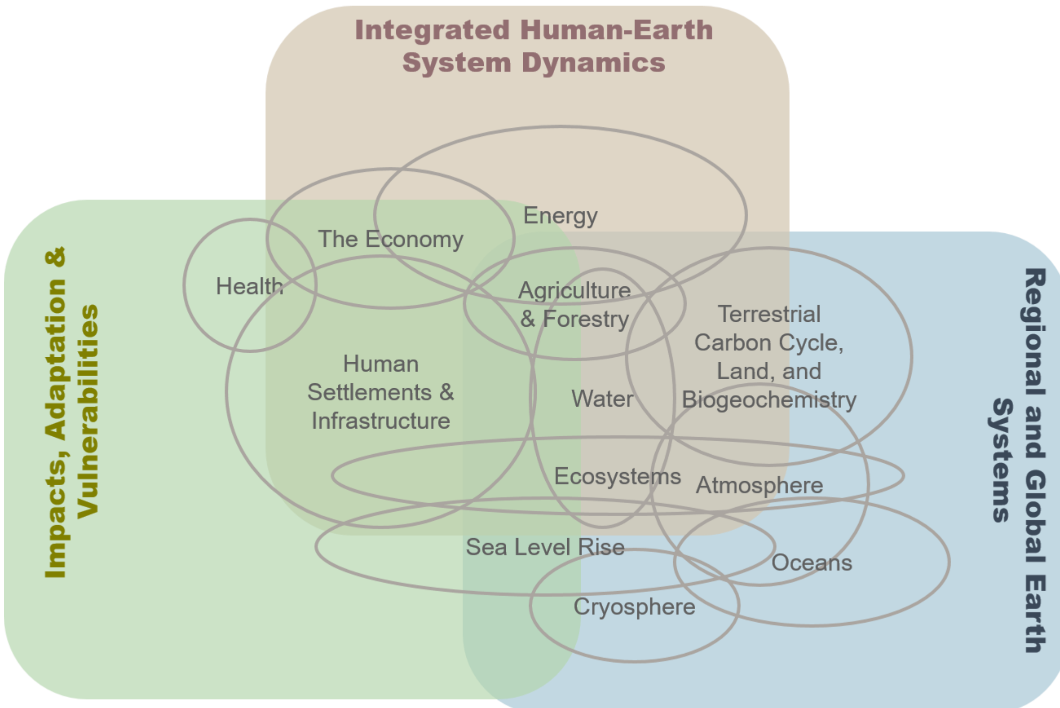
Mohamad Hejazi - Pacific Northwest National Laboratory (PNNL)

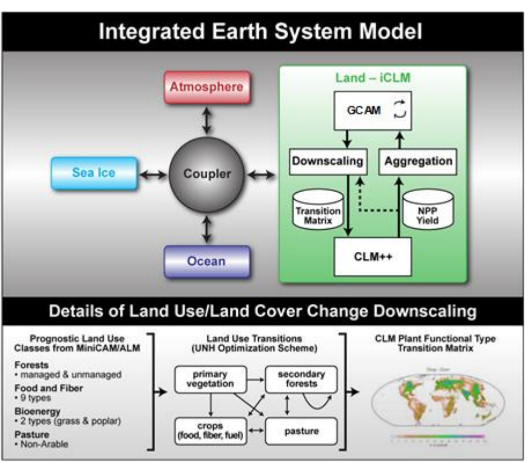
Project Participants:

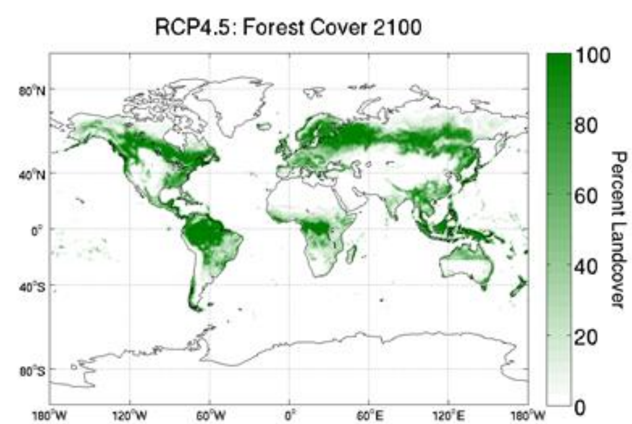
Benjamin Bond-Lamberty -Pacific Northwest National Laboratory
Katherine Calvin - Pacific Northwest National Laboratory (PNNL)
Jae Edmonds - Pacific Northwest National Laboratory (PNNL)
Corinne Hartin - Pacific Northwest National Laboratory (PNNL)
Gokul Iyer - Pacific Northwest National Laboratory (PNNL)
Son H Kim - Pacific Northwest National Laboratory (PNNL)
Page Kyle - Pacific Northwest National Laboratory (PNNL)
Robert Link - Pacific Northwest National Laboratory (PNNL)
Pralit Patel - Pacific Northwest National Laboratory (PNNL)
Steven J Smith - Pacific Northwest National Laboratory (PNNL)
Marshall Wise - Pacific Northwest National Laboratory (PNNL)
Leon Clarke - University of Maryland
Tom Wild - University of Maryland
Fernando Miralles - University of Maryland
Yuyu Zhou - Iowa State University
Jon Lamontagne - Tufts University
Pat Reed - Cornell University
Alex Ruane - Columbia University
Alan DiVittorio - Lawrence Berkeley National Laboratory
Erwan Monier - University of California Davis (UC Davis)
Ryan Sriver - University of Illinois at Urbana-Champaign
Ian Sue Wing - Boston University

Website: http://www.globalchange.umd.edu/

Integrating Human and Earth Systems Dynamics (IHESD) CONTD.



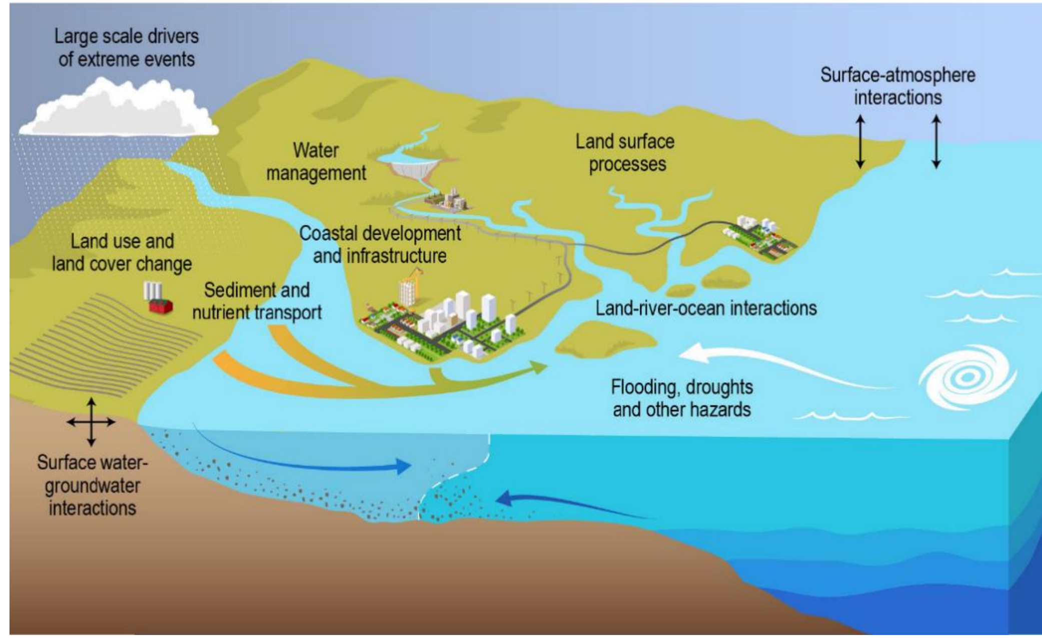




Illustrative Highlights – Global-scale Implications of Human Activities in Earth System Evolution

- A Faster Way to Explore Earth System Uncertainty
- Global Agricultural Green and Blue Water Consumption Under Future Climate and Land Use Conditions
- A Hydrological Emulator for Global Applications
- A Crop Yield Emulator for Use in GCAM and Similar Models
- A Hindcast Experiment Using the GCAM 3.0 Agriculture and Land-Use Module
- Future Hydropower Generation and Consequences for Global Electricity Supply
- Global Scenarios of Urban Density and Its Impacts on Building Energy Use through 2050
- Projecting Global Urban Area Growth through 2100 Based on Historical Time Series Data and Future Scenarios
- Reconstruction of Global Gridded Monthly Sectoral Water Withdrawals for 1971-2010 and Analysis of Their Spatiotemporal Patterns

Integrated Coastal Modeling (ICoM) Project



“Deliver a robust predictive understanding of coastal evolution that accounts for the complex, multiscale interactions among physical, biological, and human systems.”

- **Pacific Northwest National Laboratory led multi-institutional team** (LANL a strong participant)… >40% funding awarded by PNNL to others
- **Mid-Atlantic regional focus** … existing DOE capabilities, complex systems interactions, extensive data, and converging interagency activities
- **$16.2M** over three years ($5.4M/yr)
- **A “federated” approach** spanning four distinct program areas within DOE’s CESD; requires foundational work in each area <u>and</u> substantial crosscut modeling work.
- **Informs potential follow-on observational and experimental work.**

ICoM: Project Components and Topics 2020-2022

Cross-Cutting Topics

Long-term changes in flooding, drought, hypoxia, and other coastal hazards

Impacts of urbanization, development, and other land use changes on coastal systems

Regional & Global Modeling & Analysis (RGMA)

- Large-scale drivers of storms, droughts, and other extreme events
- Influence of surface-atmosphere interactions on extreme events
- Influence of land surface process on land-atmosphere interactions

MultiSector Dynamics (MSD)

- Interactions between coastal development, critical infrastructure, and natural systems
- Probabilistic natural hazard characterization
- Ability of adaptation to reduce risk or enhance resilience

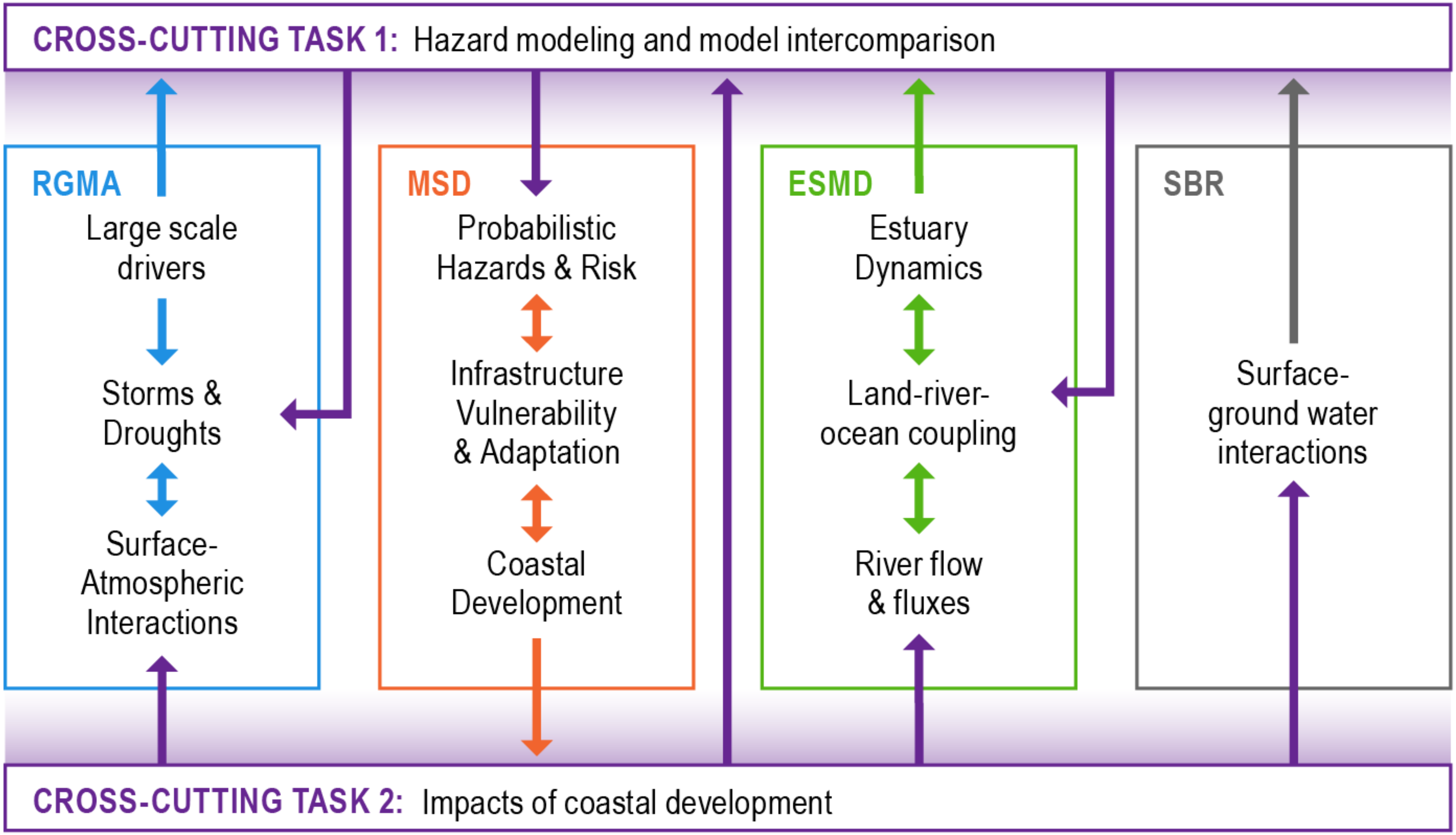
Earth System Model Development (ESMD)

- Earth system drivers of coastal flooding
- Land-river-ocean interactions affecting coastal salinity gradients
- Controls on fate and transport of sediment and nutrients

Subsurface Biogeochemistry Research (SBR)

- Influence of surface water – groundwater interactions and lateral flow on coastal flooding

ICoM: Project Crosscutting Tasks 2020-2022



ICoM: Expected Outcomes 2020-2022

New Insights

- Factors controlling mid-Atlantic extremes and how they might change in the future
- Time-evolving risks and resilience of co-evolving human and natural systems
- Role of groundwater in regional flooding, including antecedent conditions and lateral flows
- The role of coastal development in driving regional hydrological, biogeochemical, and atmospheric changes
- Relative strengths of different coastal modeling approaches

New/Enhanced Capabilities

- Regionally refined global-to-coastal-scale Earth system model
- Model of coastal development patterns
- Endogenous adaptation in coastal infrastructure systems
- Integrated hydrologic models for the Delaware and Susquehanna basins
- High-resolution simulations of mid-Atlantic flooding, droughts, and hypoxia
- Metrics for land surface processes

ICoM: Potential Future Work (and/or Partnership Opportunities with Other Projects/Programs/Agencies)

Additional Stresses

- Coastal erosion, floodwater scouring
- Acidification, saltwater intrusion
- Ice storms, ice dams, etc.
- Compound stresses

Additional Impacts

- Compromised infrastructure due to saltwater intrusion, erosion, and wave impacts
- Salinity-induced ecosystem mortality and impacts on biogeochemistry

Additional System Dynamics

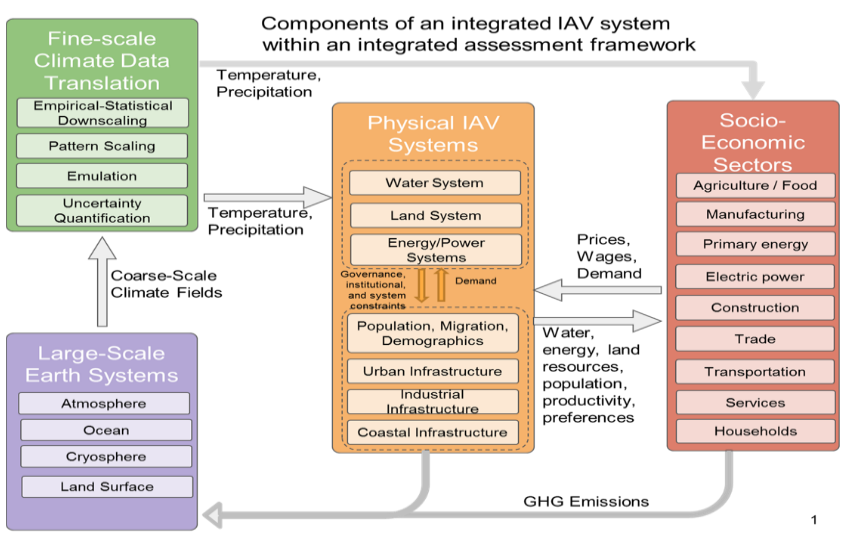
- Vegetative dynamics
- Ecogeomorphology
- Additional infrastructure systems (e.g., transportation)

Additional Geographic Contexts

- Use tools and lessons learned from the mid-Atlantic in other regions
- Establish typologies of coastal systems
- Identify data gaps/observational needs

Program for Coupled Human Earth Systems (PCHES) Cooperative Agreement

Research in support of a next-generation integrated suite of science-driven modeling and analytic capabilities, examining, challenging, and serving as an innovation engine for the leadership-class team-based models such as developed by IM3, MSD, and DOE's E3SM. The effort focuses on evaluations and development of modeling approaches, constructs, coupling mechanisms, core component development, sensitivity analysis and, at the most fundamental level, analysis of what complexity, details, and scales matter for different questions, topics, and research/user communities.



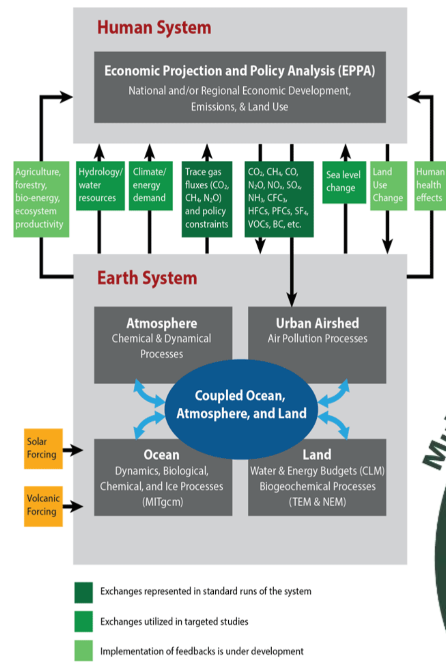
Principal Investigator:
John Weyant - Stanford University
Karen Fisher-Vanden - Pennsylvania State University
Robert Nicholas - Pennsylvania State University

Project Participants:
Noah Diffenbaugh - Stanford University
David Lobell - Stanford University
Christopher Forest - Pennsylvania State University
Murali Haran - Pennsylvania State University
Klaus Keller - Pennsylvania State University
Jim Shortle - Pennsylvania State University
Mort Webster - Pennsylvania State University
Doug Wrenn - Pennsylvania State University
Thomas Hertel - Purdue University
Ian Sue Wing - Boston University
Steve Frolking - University of New Hampshire
Richard Lammers - University of New Hampshire
Alex Prusevich - University of New Hampshire
Patrick Reed - Cornell University
Wolfram Schlenker - National Bureau of Economic Research

https://www.pches.psu.edu/

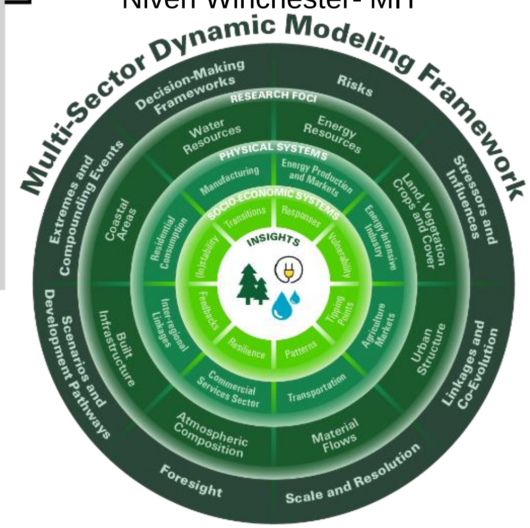
Integrated Global Systems Modeling (IGSM) Cooperative Agreement

Develop and focus enhancements on the IGSM framework, built around an Earth system model, an economic model of human activity, and a growing set of components that link economic activity to natural resources affected by environmental change. By focusing research on risks of extremes and compounding events through integrated modeling of physical and socioeconomic systems, the research advances insights on the vulnerabilities and resilience in a region, potential tipping points, and responses and feedbacks throughout these systems. With a regional focus, this project explores two interconnected regions in the United States (the Lower Midwest and Gulf Coast), three systems (water/land, energy infrastructure, and coastal communities), and four economic sectors (transportation, agriculture, industry, and energy)—all subject to compounding extreme events and more gradual transitions driven by long-term forces and patterns of development. The chosen regions provide interesting natural (river), built (levee system, transportation network), and economic (fuels, electricity, transportation, ports) connections between the regions.



Principal Investigator:
Ron Prinn- MIT
John Reilly - MIT

Project Participants:
Adam Schlosser – MIT
Sergey Paltsev- MIT
Chien Wang- MIT
Stephanie Dutkeiwicz - MIT
Erwan Monier- MIT
Niven Winchester- MIT



Website: https://globalchange.mit.edu/research/research-projects/integrated-framework-modeling-multi-system-dynamics

HyperFACETS Cooperative Agreement

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Hyperion

PI: Paul Ulrich

Development of a comprehensive regional hydroclimate data assessment capability focused on feature-specific metrics and stakeholder-relevant outcomes. Additionally, the effort seeks to leverage this assessment capability to improve our ability to predict these outcomes, by identifying the process-level drivers of outcome biases and evaluating the most appropriate and efficient ways to couple climate models, hydrologic models, and **models of human impacts (e.g., localized irrigation influences)**

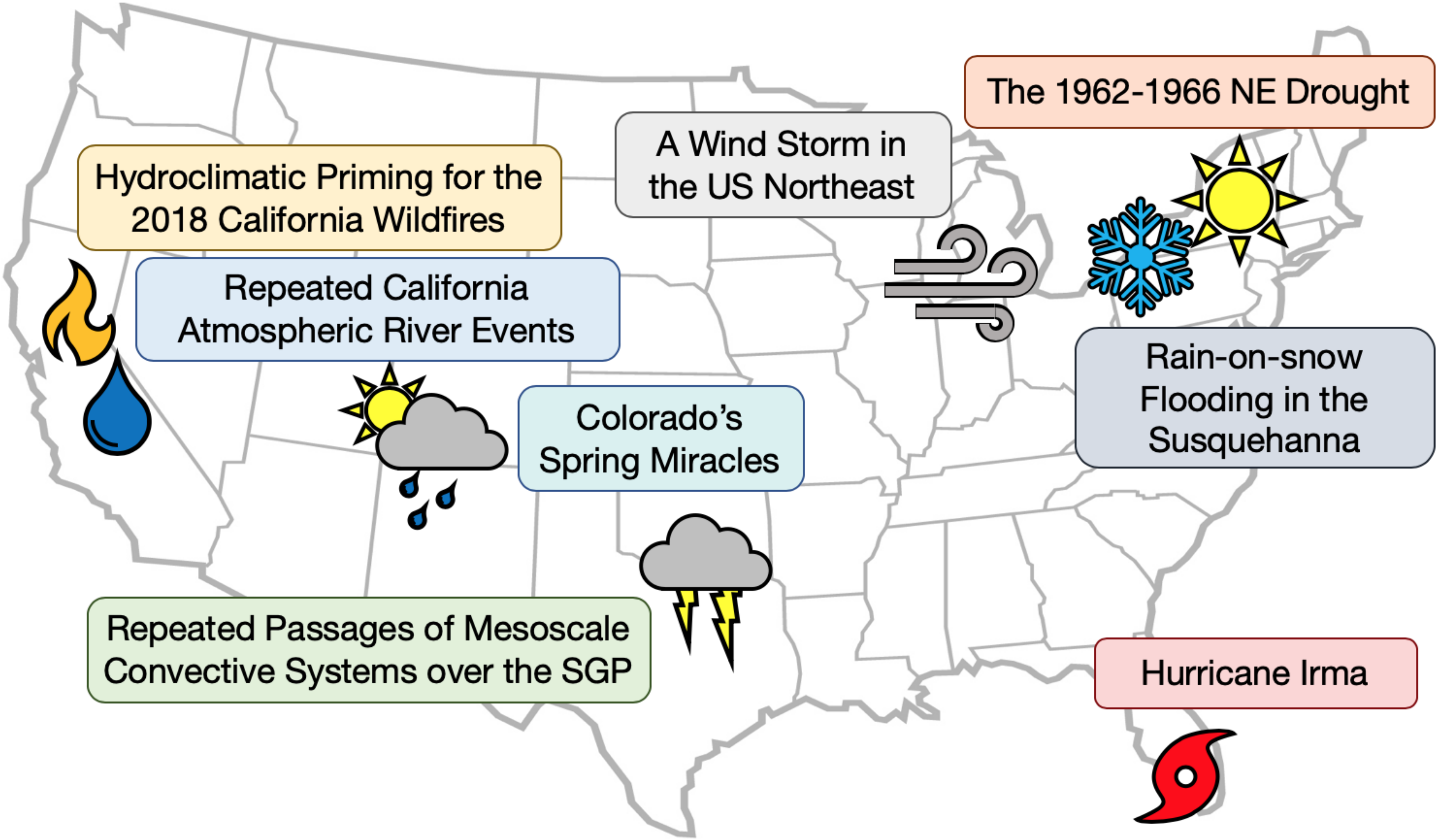
FACETS

PI: Bill Gutowski

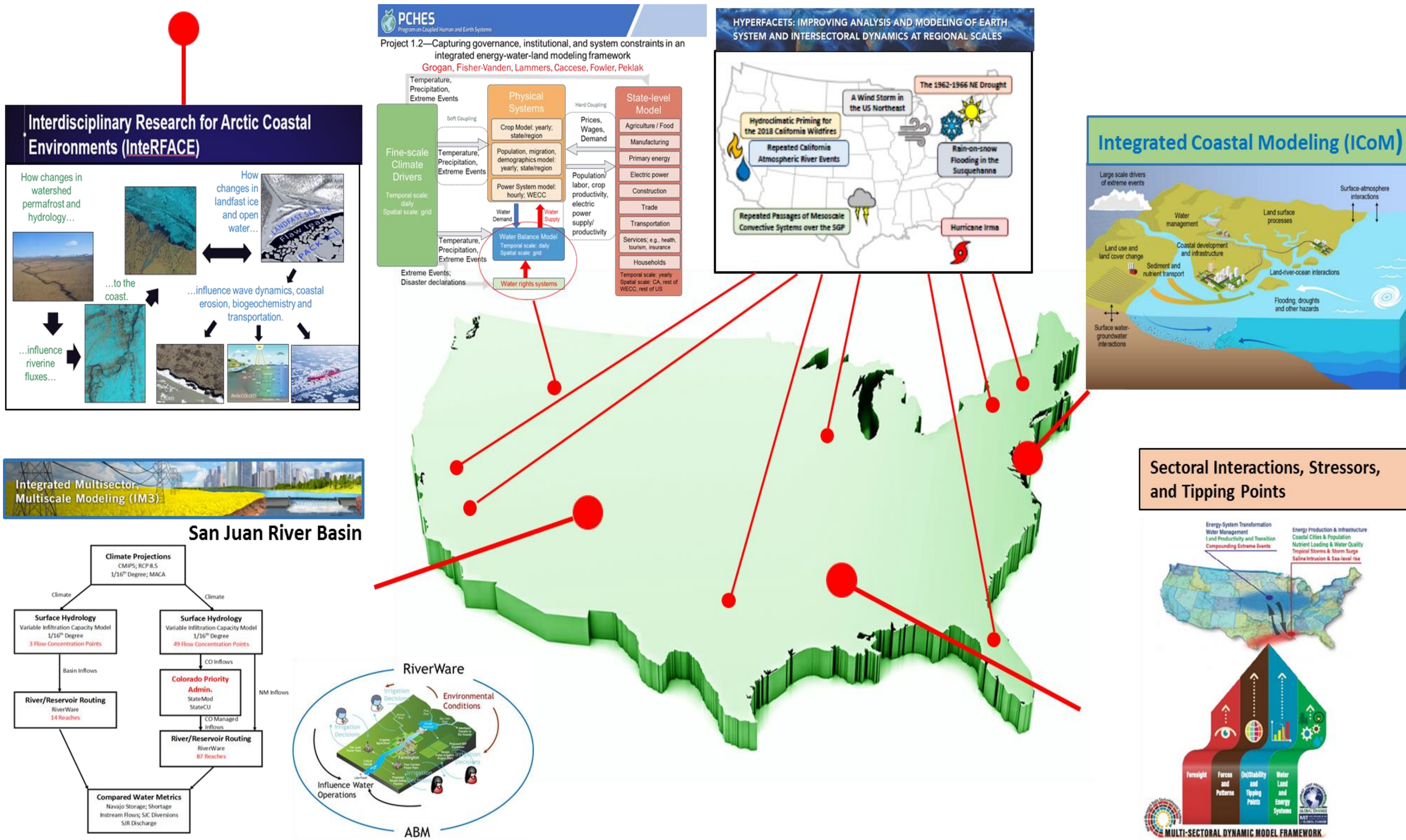
Development of a hierarchical model evaluation framework informed by different uses of climate models and their output by climate scientists and stakeholders for planning and managing resources. Examination of a suite of different modeling methods and design structured, hierarchical experiments for regional analysis that feature baseline simulations across a range of spatial resolutions and modeling approaches. Some of these simulations will focus on the impacts of future land use and **land cover changes associated with food and bioenergy crop production and urbanization, and expansion of wind turbine deployment, which highlight specific challenges for modeling the energy-water-land nexus**

HyperFACETS Cooperative Agreement CONTD.

Storylines



Overall, MSD is addressing a growing range of topics…and geographies…of interest

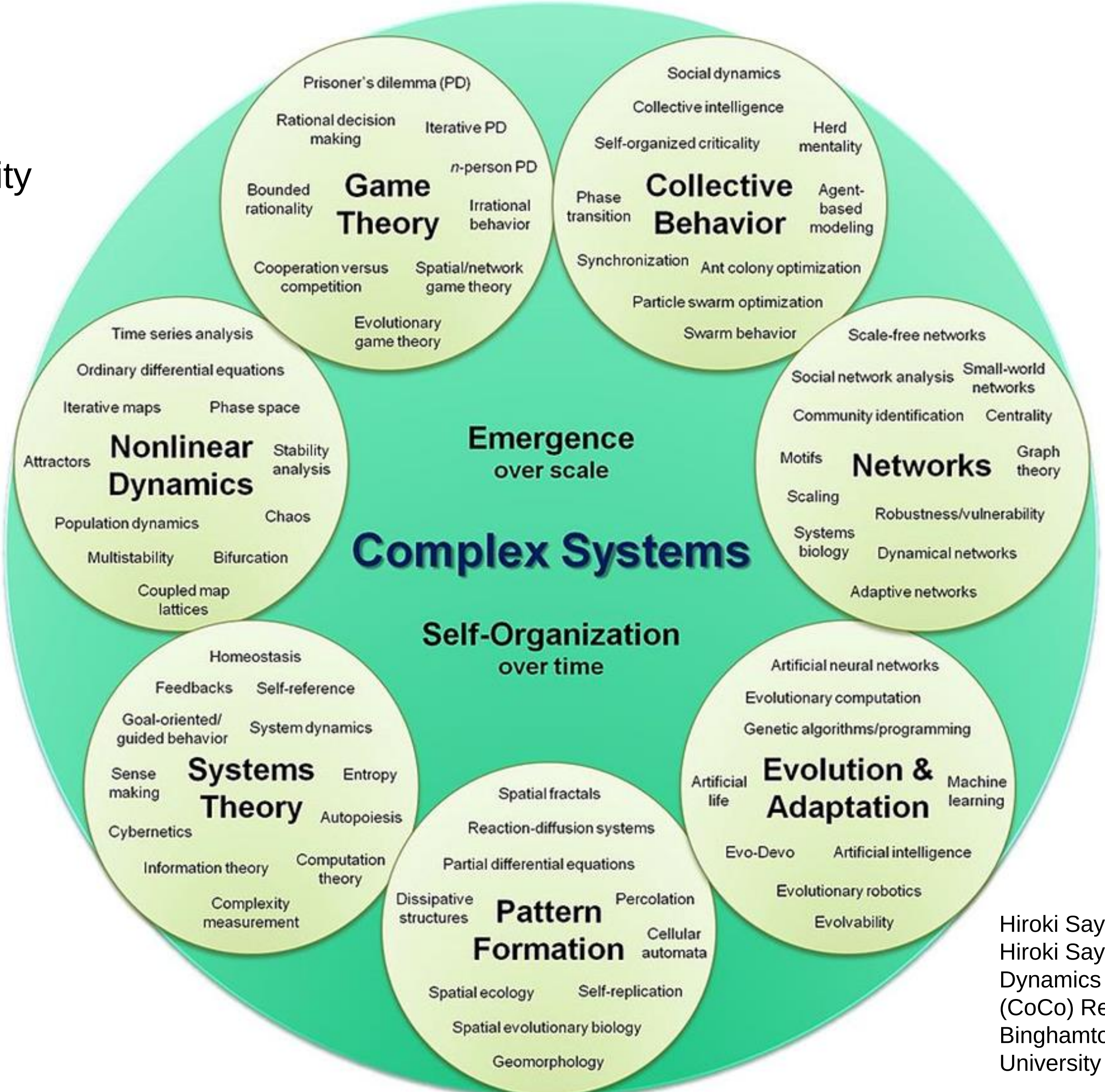


Future directions

- **Functional, collaborative community-of-practice and working group structure**
- **Hierarchical frameworks** and use-inspired tools (emulators, sensitivity research, etc.)
- **Distributed science mechanisms** (i.e., open source models, software couplers, interoperability, modular methods, community data and computation
- **Complexity theory and science** (networks, collective behavior, evolution and adaptation, pattern formation, systems theory, machine learning, etc.)
- **Scenario methods and development** with implications for uncertainty framing/analysis, complex storylines, modeling experiments, and more.
- **Model resolution and fit-for-purpose process details** across spatial and temporal scales (e.g., energy, water, land, economics, population, land use, technology
- **Significant coupled systems behaviors**, such as found among energy, water, land and socioeconomic systems with non-linear responses, e.g., induced by extremes

Moving to incorporate…..

Creation of a new, formal MSD community of practice is working to jumpstart!

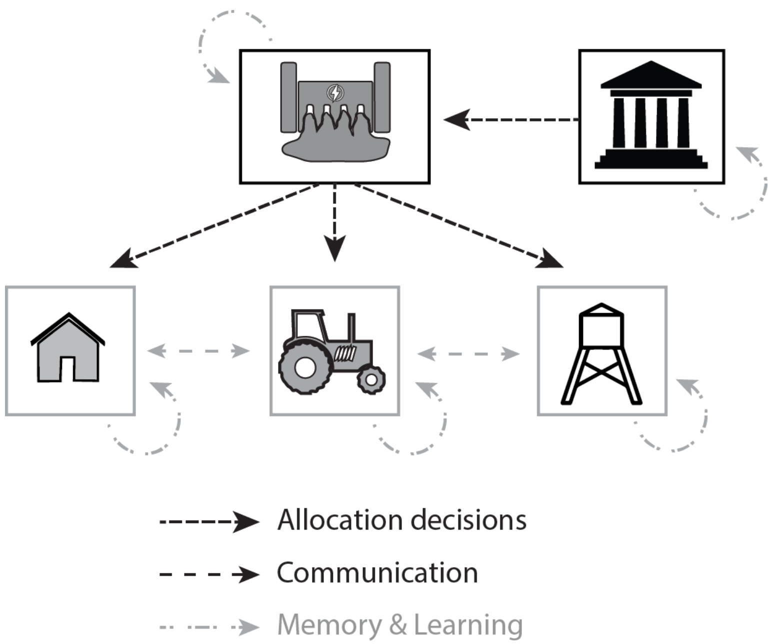


Hiroki Sayama, D.Sc. - Created by Hiroki Sayama, D.Sc., Collective Dynamics of Complex Systems (CoCo) Research Group at Binghamton University, State University of New York

Work in behavioral economics and now agent-based modeling is foundational

Agent-Based Modeling

- Agents can represent individuals or organizations
- Interact with each other and the environment
- Adaptive behavior (learning)
- Various decision-making strategies
- Can reflect social or institutional network structure



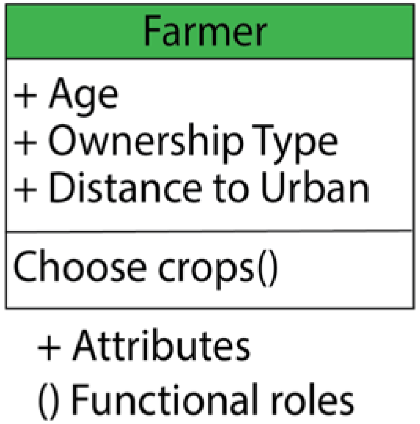
*Following slides courtesy of IM3…Alejandro Flores

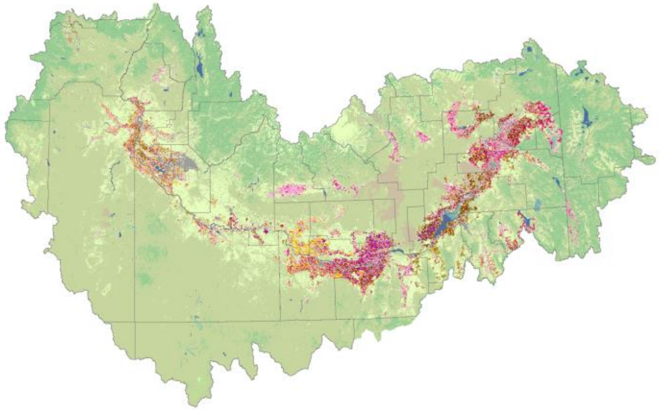
For example…

Linking socio-economic drivers of LULCC

Janus:

- Object-oriented python framework (modular and extensible)
- Probabilistic decision-making based on environmental and socioeconomic information
- Incorporation of social networks to examine emergent adaptive behavior



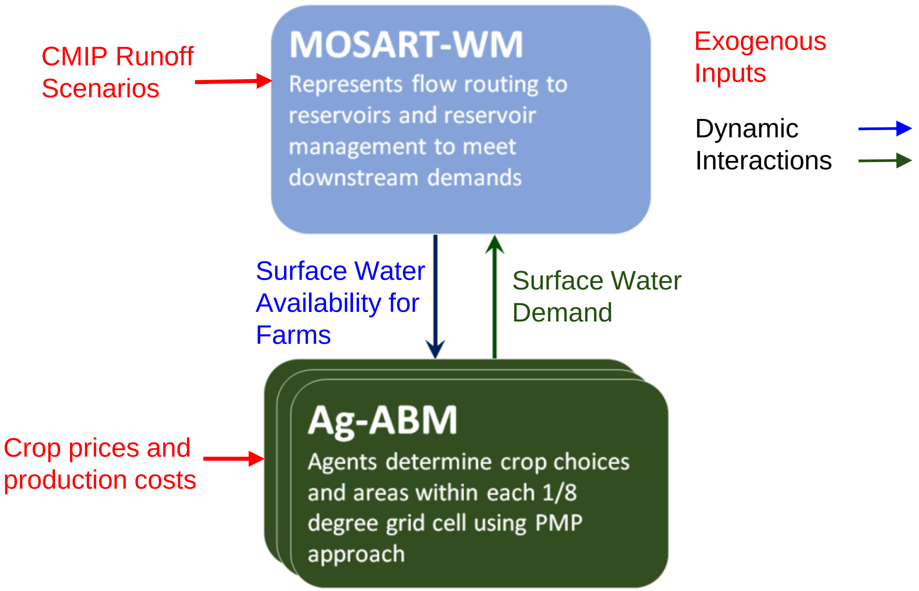


2,800-25,000 farmer agents represented in tl Snake River Basin at 1-km resolution

And…

MOSART-WM-ABM Modeling Approach

- Regional hydrology model integrated with farm crop choice ABM at CONUS scale
- Farms maximize profit, merging economic theory with data-driven calibration
- The approach is readily applicable across scales, here applied at ⅛ degree resolution (~50k farm agents)

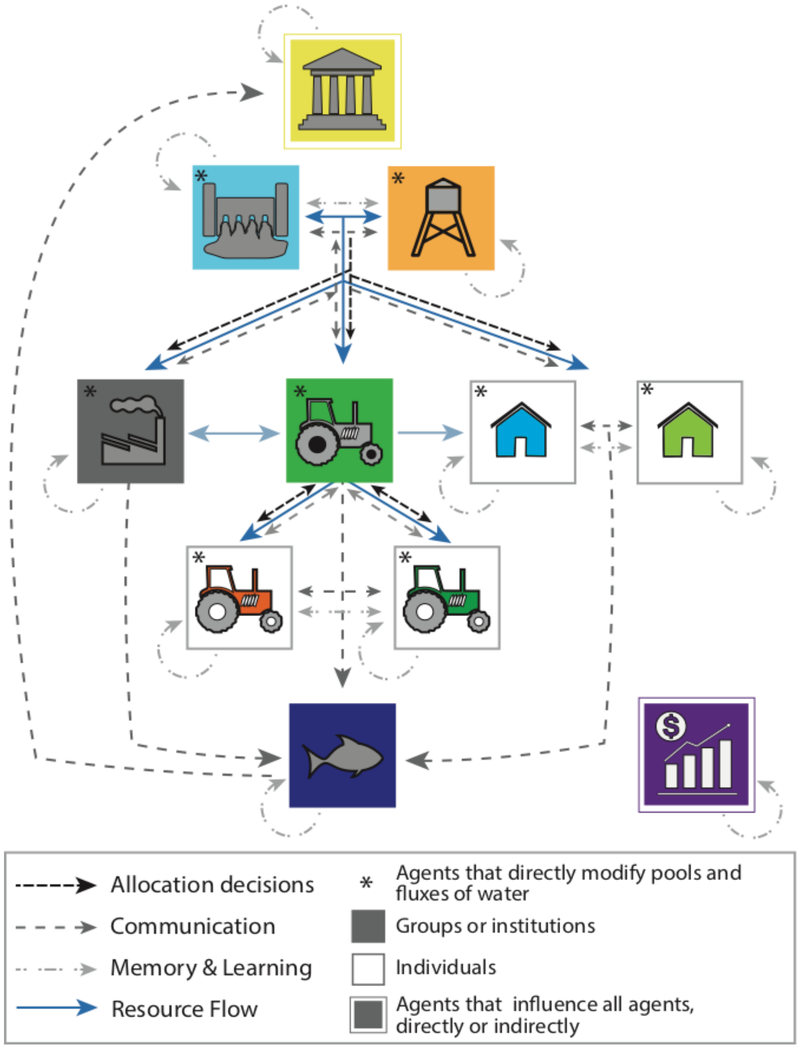


- Calibrated based on observed crop patterns (CDL) and USDA economic datasets over CONUS

Agent based modeling research gaps and next steps

Research gaps and next steps

- Development of standardized agent types and documentation standards
- Implementation of new agent types
  - Resource suppliers: water / energy utilities
  - Resource users: domestic water users
  - Resource regulators: water allocation institutions
- Implementation of agent interactions between sectors (e.g. energy-water)
- Groundwater model coupling



Decision/behavioral examples/publications…

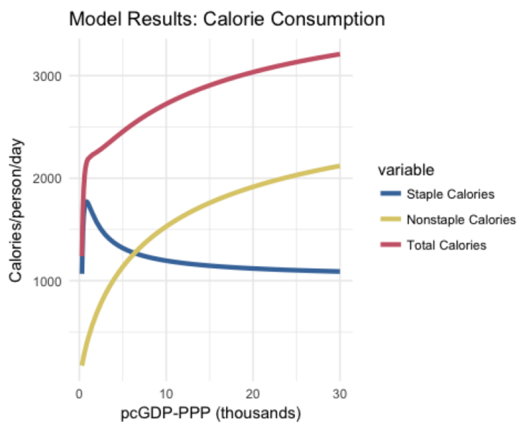
IHESD: A global food demand model for the assessment of complex human-Earth systems

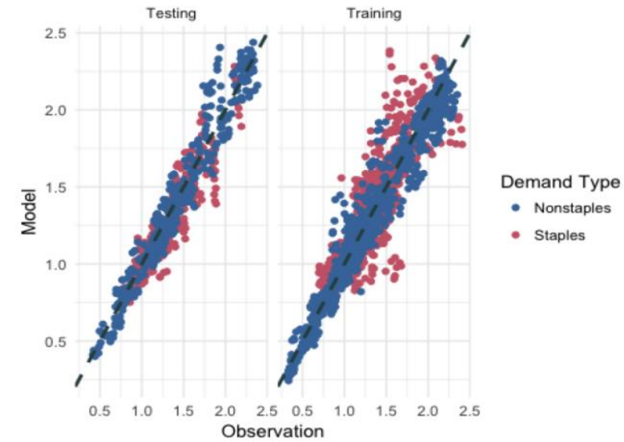
Objective

- Develop and test a new consumer choice model to assess food demand, an important determinant of terrestrial systems.

Approach

- **Develop a new model of consumer choice that addresses the classic economic problem of saturation of food demands at high income levels.**
- Develop a data base to estimate the model.
- Apply advanced statistical techniques to estimate model parameters, cross-validate and bias correct to ensure robust predictions.





A long-standing economic problem, is the saturation of food demands at high income levels. This problem was successfully addressed with a new consumer demand model. Left panel shows the relationship between income and food demands in the model. Model parameters were estimated using global cross-section, time-series observations. Right shows the results from cross-validation with bias correction.

Impact

- **A new demand system was developed for numerical simulation of food demands that saturate at high per capita incomes.**
- Advanced statistical techniques were employed to estimate model parameters.
- The model will be used in the Global Change Assessment Model (GCAM) to provide a richer and more robust characterization of interactions between human and physical Earth systems.

Edmonds, J, R.P. Link, S.T. Waldhoff and R. Cui. 2017. “A global food demand model for the assessment of complex human-Earth systems.” *Climate Change Economics* 8(4):1750012 (22 pages). DOI: 10.1142/S2010007817500129

IM3: Sensitivity of Western U.S. power system dynamics to droughts compounded with fuel price variability

Objective

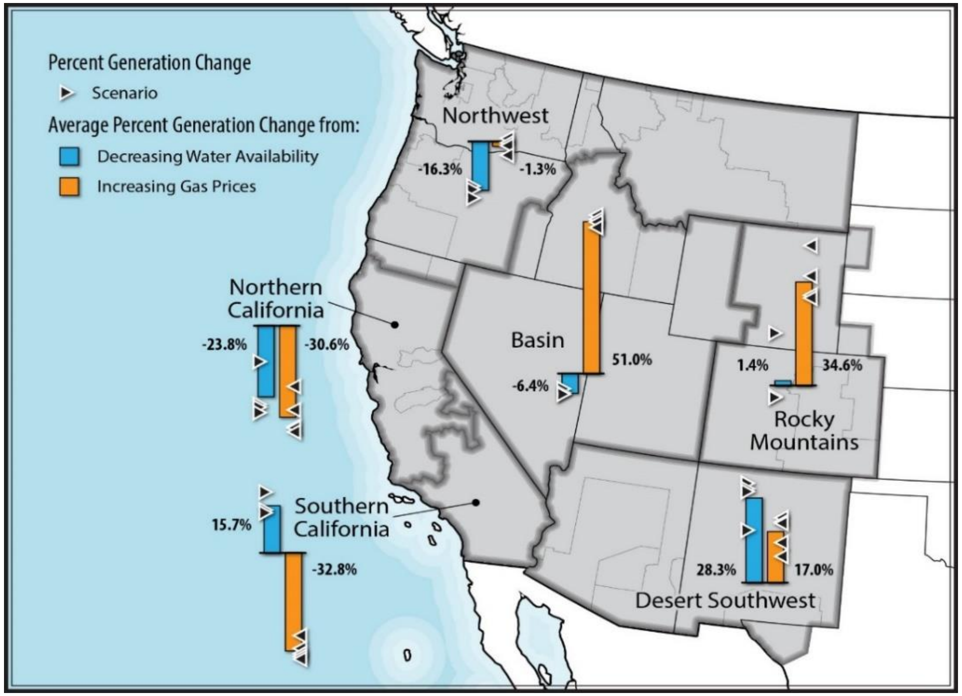
- Use innovative model coupling across sectors to understand tradeoffs and tipping points of water-related stresses compounded with market stresses related to fuel price volatility for the western U.S. power grid

Approach

- Apply high-resolution power system model simulations to identify a range of water availability cases
- Combine hydrology scenarios with four separate natural gas price scenarios to capture historical and future price volatility
- Evaluate power system impacts and regional trends using high-resolution production cost model

Impact

- Research sheds light on the tradeoffs and tipping points of water-related stresses compounded with stresses related to fuel price volatility
- Study reveals that water-related stresses can have the same magnitude of impacts on grid operations as natural gas price volatility
- Regional responses to simultaneous stresses can augment/offset stresses analyzed in isolation



The map indicates the sensitivity of western U.S. power system generation to droughts compounded with fuel price variability. Analysis of six major subregions showed that the effects of water availability and fuel prices could be of the same magnitude and that the sensitivity to drought versus higher gas prices depends on the sub-regional generation mix.

O'Connell M, N Voisin, J Macknick, and T Fu. 2019. "Sensitivity of Western U.S. Power System Dynamics to Droughts Compounded with Fuel Price Variability." *Applied Energy* 247:745–754, https://doi.org/10.1016/j.apenergy.2019.01.156.

IHESD: Global agricultural green and blue water consumption under future climate and land use conditions

Objective

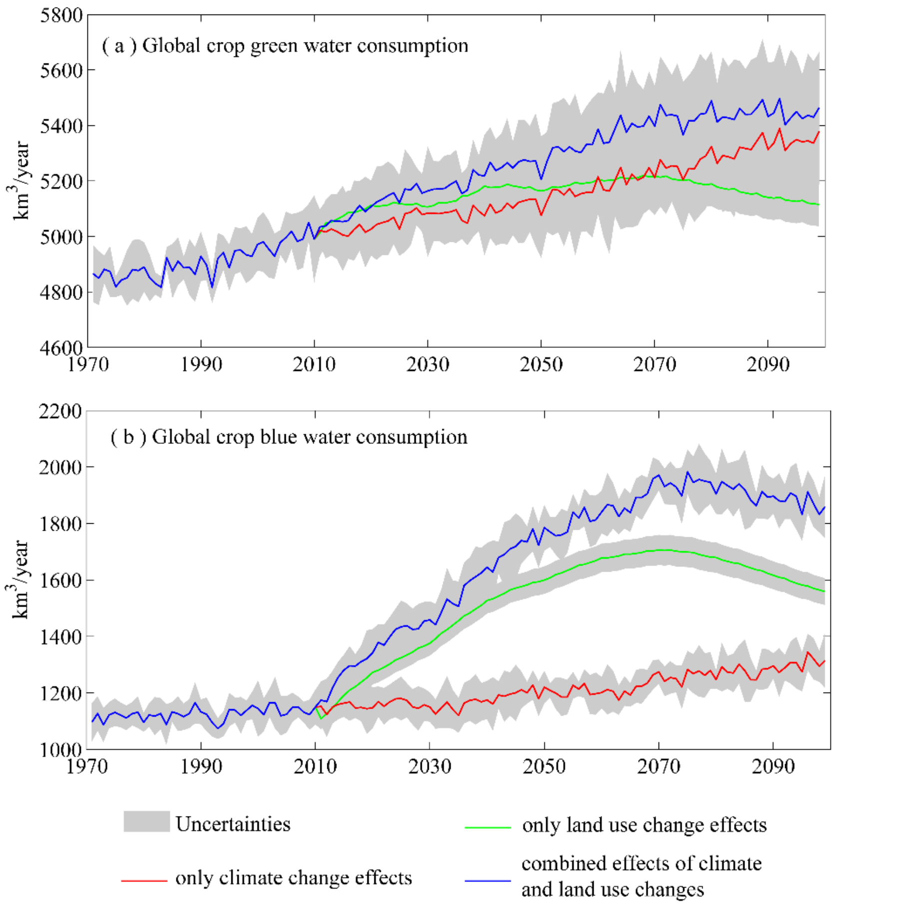
- Estimate global crop consumption of green water (precipitation) and blue water (irrigation) during the 21st century
- Determine individual and combined effects of future climate and land use conditions on crop water consumption

Approach

- Incorporate a crop-water use module into Global Change Assessment Model (GCAM) system
- Design three control experiments to separate effects of climate and land use on future crop water consumption

Impact

- Global crop green and blue water consumption are projected to increase by about 12% and 70%, respectively, by the 2090s
- Shifts in crop green and blue water consumption are mainly driven by climate and land use, respectively
- Study improved understanding of how future climate and land use conditions can affect global agricultural water consumption, which is critical to devise effective adaptation strategies for securing future food and water needs sustainably



A time series for the period 1971–2099 shows individual and combined effects of climate and land use changes on future global crop green and blue water consumption.

Huang Z, M Hejazi, Q Tang, CR Vernon, Y Liu, M Chen, and KV Calvin. 2019. “Global agricultural green and blue water consumption under future climate and land use changes.” *Journal of Hydrology* 574:242–256, https://doi.org/10.1016/j.jhydrol.2019.04.046.

PCHES: Robust decision making (RDM) is used to inform idealized port investment decisions considering changes in flood risk due to sea-level rise.

Objective

Utilize probabilistic approaches to address two questions applied to investment decisions at the Port of Los Angeles:

(1) Under what future conditions would hardening of coastal facilities against extreme flood scenarios at the next upgrade pass a cost-benefit test?

(2) Do sea-level rise projections and other information suggest such conditions are sufficiently likely to justify such an investment?

Approach

Characterize deeply uncertain climate change projections of sea-level rise and impacts using Robust Decision Making analysis and full probabilistic approaches.

Impact

- Results highlight the highly-localized and context dependent nature of applying Robust Decision Making methods to inform investment decisions.

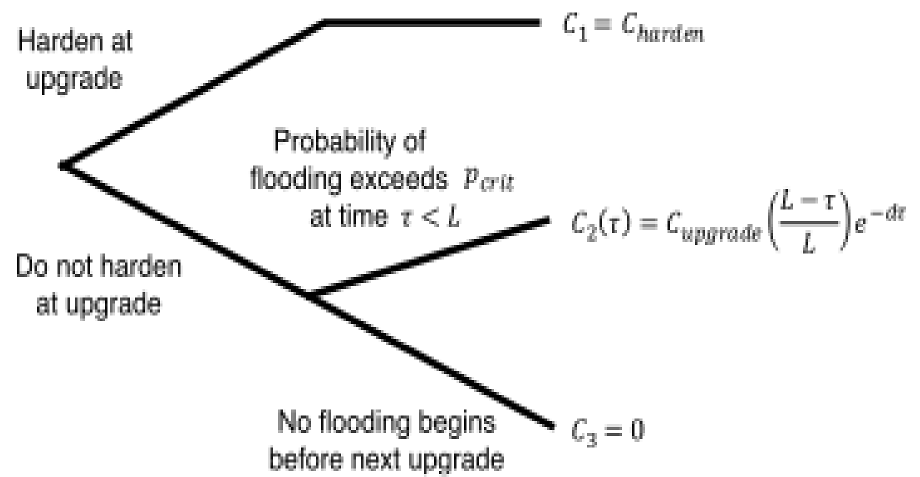
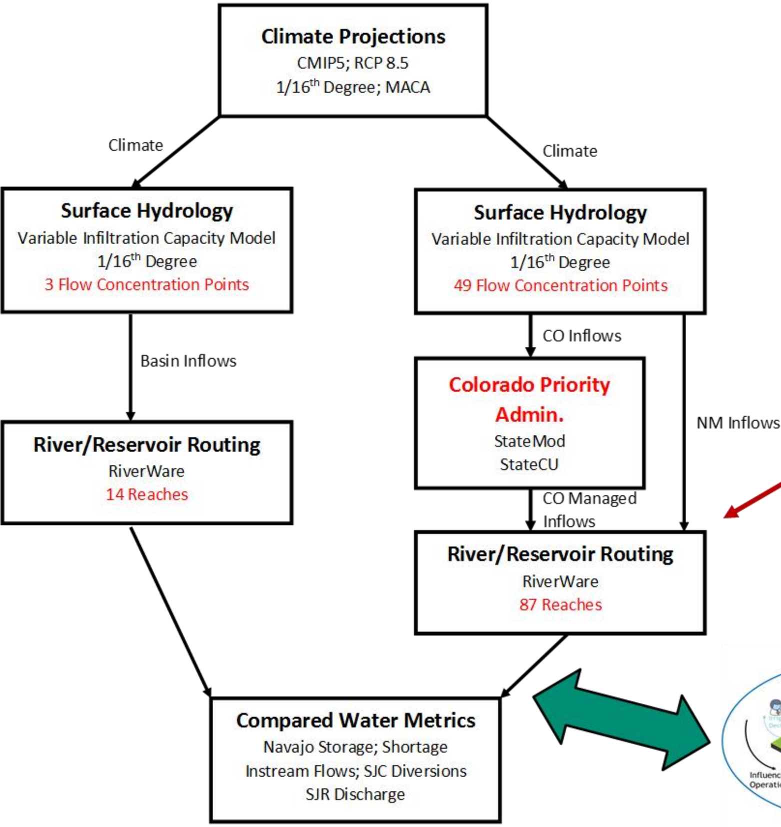


Figure: Simplified representation of Port of LA's decision regarding whether or not to harden its terminal at its next upgrade and the costs resulting from its choices.

IM3: Multi-scale analysis drives understanding of electric grid vulnerability to water shortages

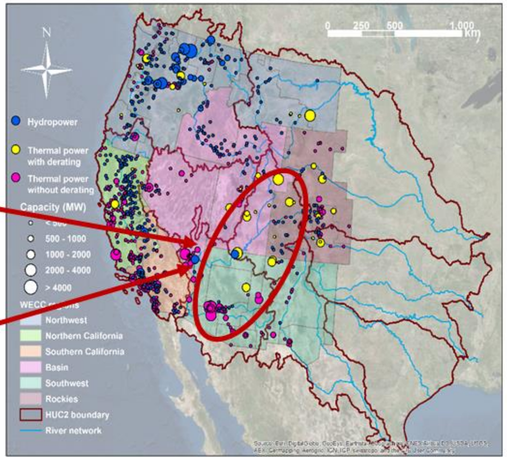
San Juan River Basin



San Juan River Basin

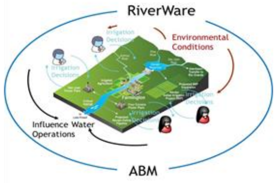
VIC-StateMod-RiverWare

San Juan River Basin

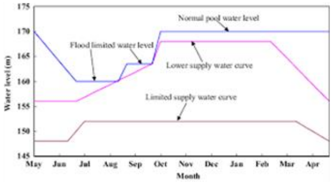


VIC-MOZART-WM

- Identify metrics
- Verify comparable simulations
- Interpret differences
- Develop scaling rules



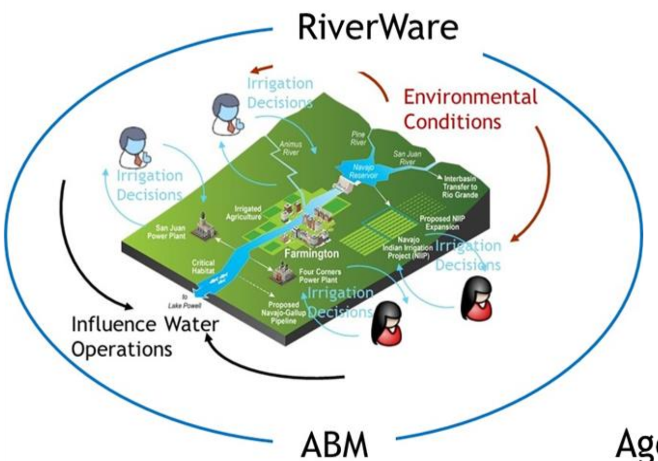
Agent Scaling



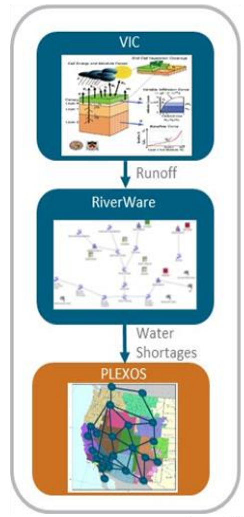
Emulators

IM3: Multi-scale analysis drives understanding of electric grid vulnerability to water shortages…the *downstream response*

Agent Response

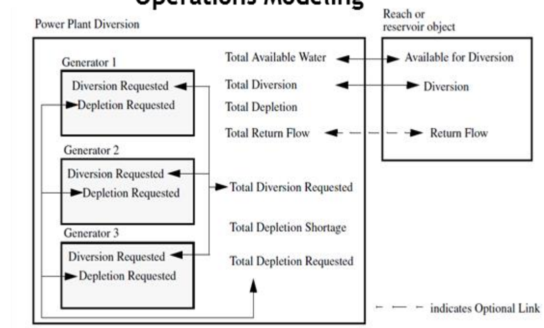


Incorporating risk, perception, previous experiences and environmental information in the decision-making process

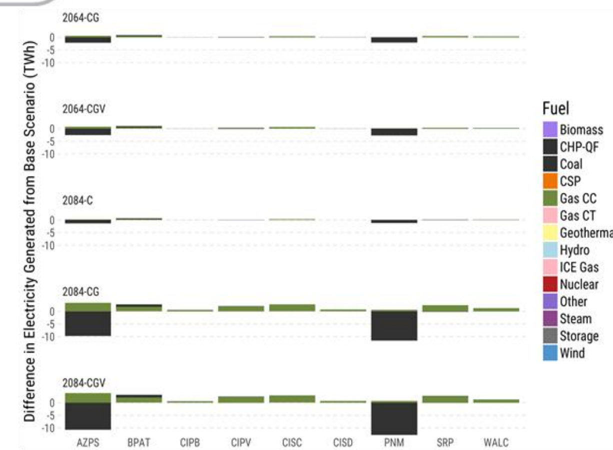


Grid Response

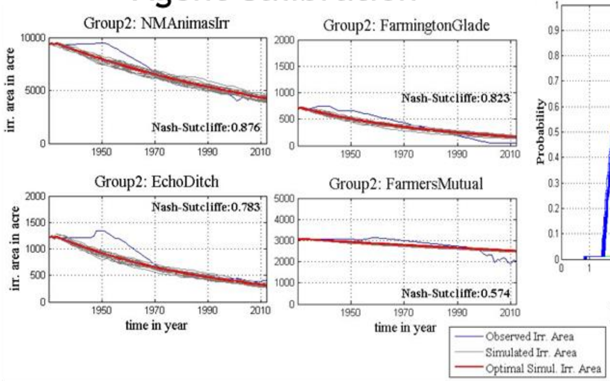
Tightly Coupling Power Plant - River Operations Modeling



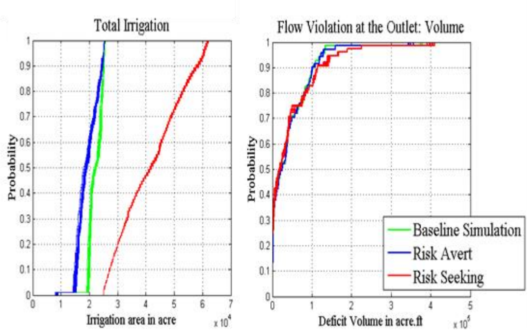
Regional WECC Generation Differences due to Localized Water Shortages



Agent Calibration



Agent Risk Perception



Quantifying the adaptive water management decision in the San Juan River Basin under climate change
Yi-Chen Ethan Yang, Lehigh University, Bethlehem, PA, United States, Kyongho Son, University of California, Santa Barbara, Santa Barbara, CA, United States and Vincent Carroll Tidwell, Sandia Natl Laboratories, Albuquerque, NM, United States **Poster on Monday afternoon**

Climate-Water Impacts on Interconnection-Scale Electricity System Planning
Stuart Michael Cohen, Ana Dyreson, Jordan Macknick, Ariel Miara, Vincent Carroll Tidwell, Nathalie Voisin, Sean William Donald Turner and Michael Bailey, **Poster on Tuesday afternoon**

IM3: Irrigation practices affect regional monsoon precipitation

Objective

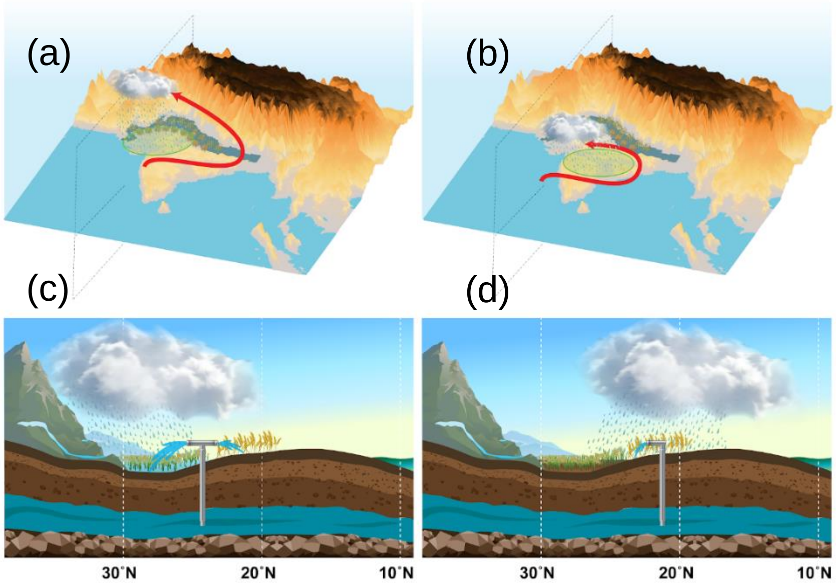
- Understand the effects of land and water management practices on monsoon circulation and extreme rainfall.

Approach

- Implement modules into Weather Research and Forecasting model coupled to the Community Land Model version 4 (WRF-CLM4) to represent irrigation, groundwater pumping, and the bio-geophysical effects of flooded paddy fields.
- Employ the enhanced WRF-CLM4 to simulate the impact of agricultural water management practices using numerical experiments.

Impact

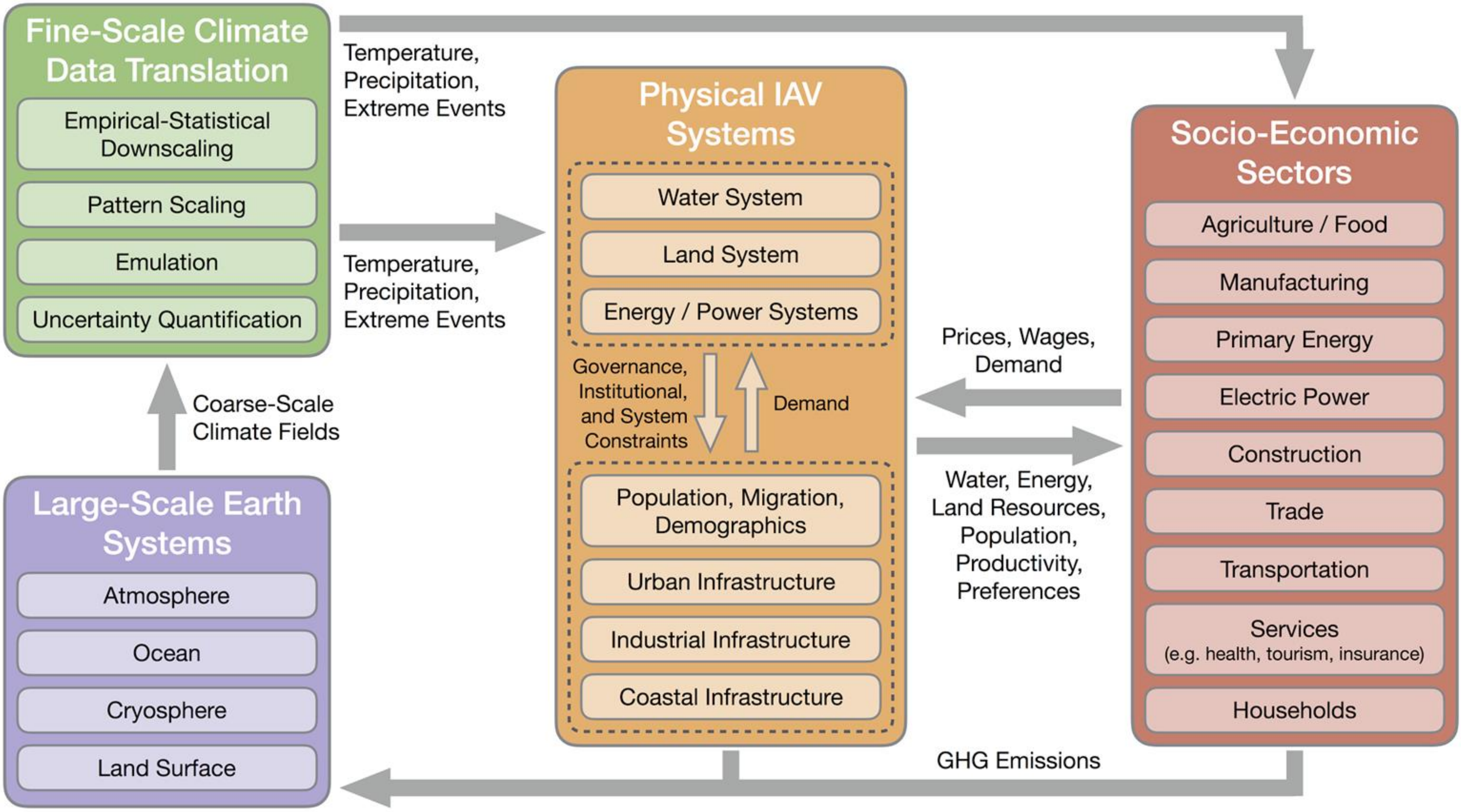
- Confirmed through modeling that excess irrigation over northern India causes a northwestward shift in monsoon rainfall and intensifies widespread extreme precipitation over Central India, consistent with observations.
- Demonstrated that it is important to represent land management and irrigation practices accurately in Earth system and weather models.



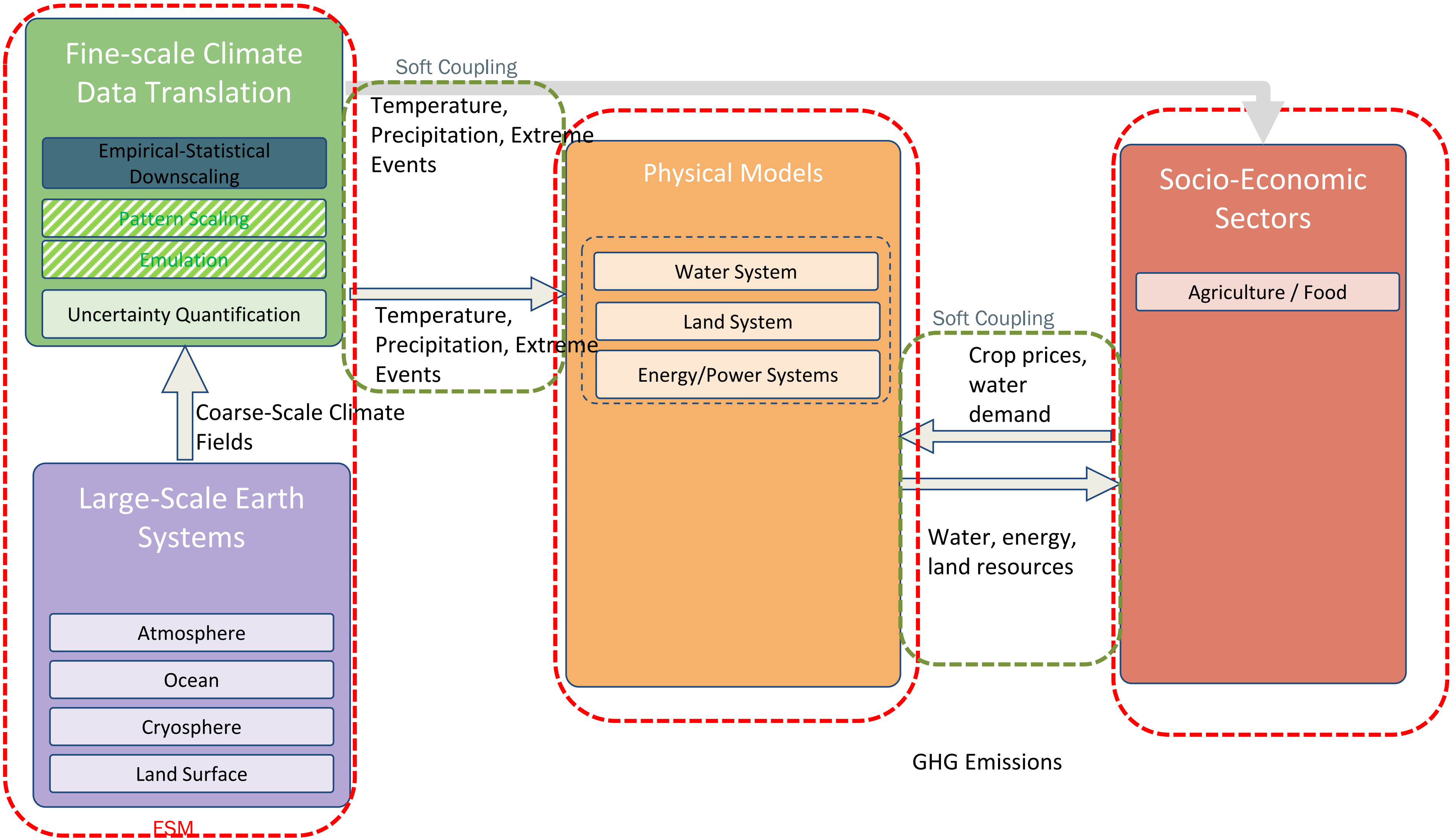
Experiments with realistic representation of unmanaged irrigation and paddy cultivation over north-northwest India exhibit an increase in the late season terrestrial monsoon precipitation and intensification of widespread extreme events over Central India (panels a and c), compared to the case in which irrigation is managed based on crop water demand (panels b and d). This finding is consistent with changes in observations.

Devanand A, M Huang, M Ashfaq, B Barik, S Ghosh. 2019. "Choice of Irrigation Water Management Practice affects Indian Summer Monsoon Rainfall and its Extremes." *Geophysical Research Letters,* 46 (15): 9126-9135, *https://doi.org/10.1029/2019GL083875* .

PCHES: Components of an integrated framework for modeling coupled energy-water-land systems dynamics

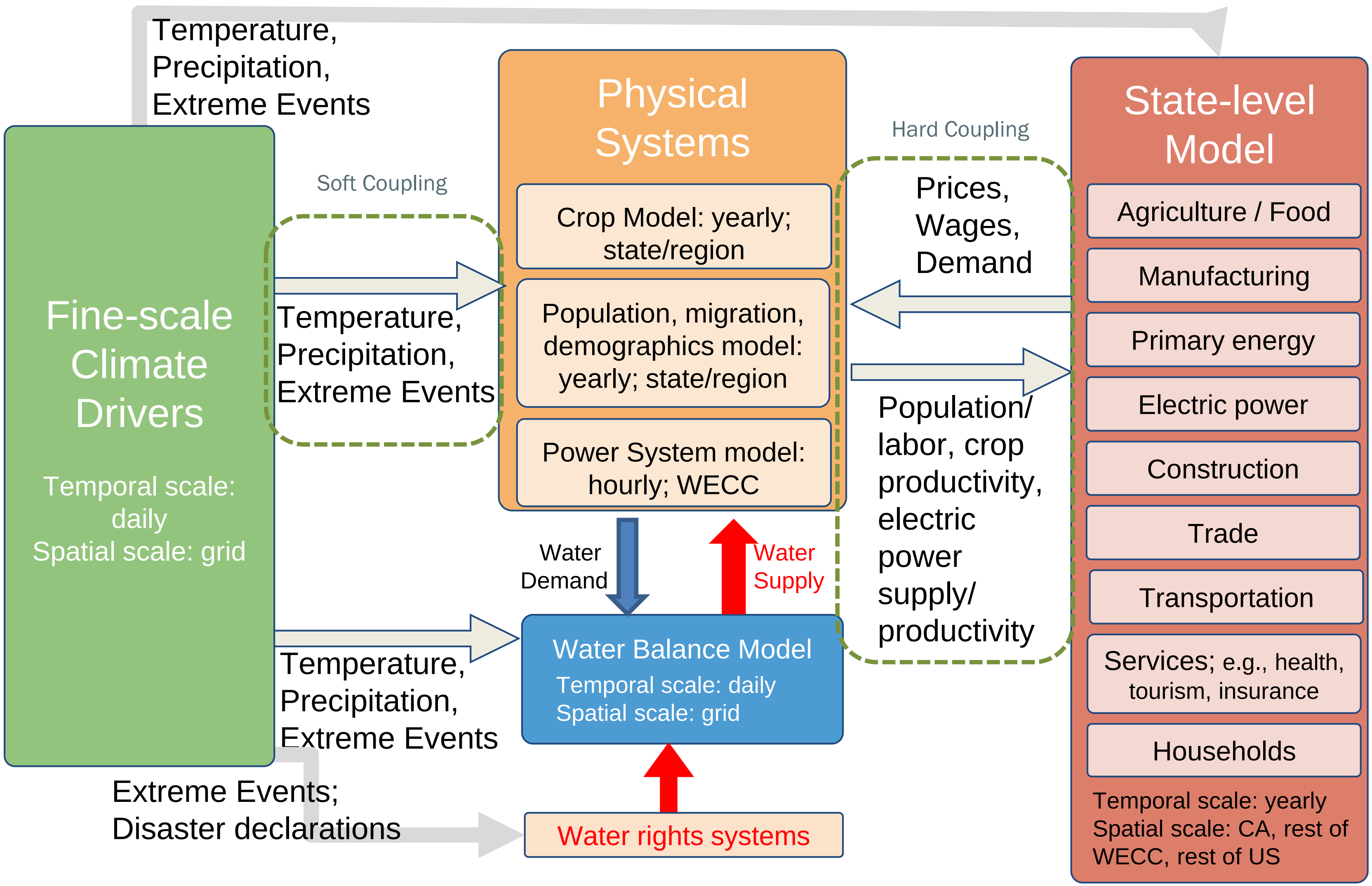


PCHES: Variant 1 - Gridded modeling of integrated energy-water-land systems dynamics Hertel (lead), Grogan, Haqiqi, Lammers, Liu, Schlenker, Sun, Valqui, Webster

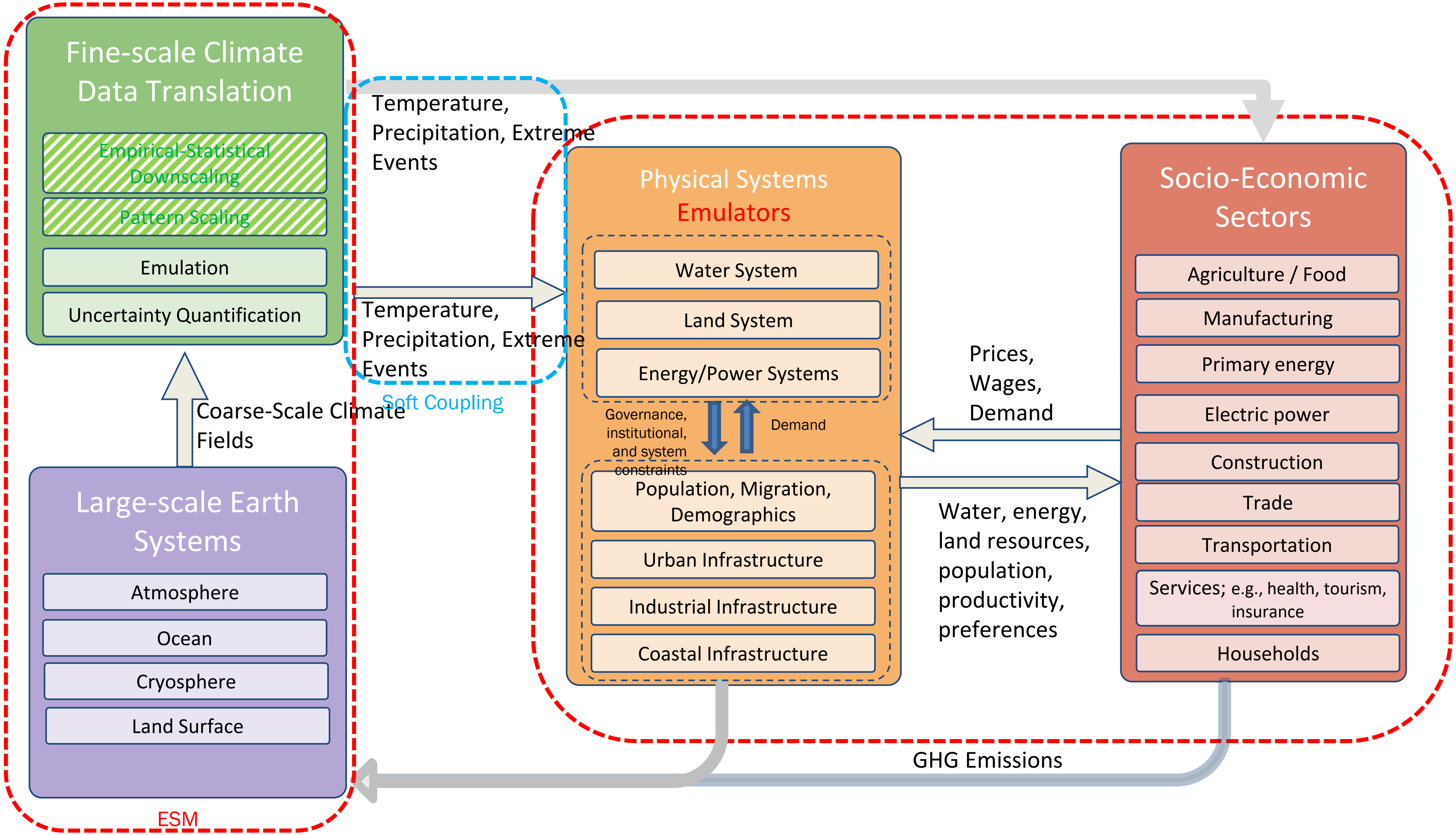


PCHES: Variant 2 - Capturing governance, institutional, and system constraints in an integrated energy-water-land modeling framework

Fisher-Vanden (lead), Caccese, Fowler, Frolking, Grogan, Jayasekera, Kumar, Lammers, Nicholas, Peklak, Perla, Webster, Wrenn



PCHES: Variant 3 - Global modeling of integrated energy-water-land systems dynamics Sue Wing (lead), Mansur, De Cian, Mansur, Mistry, van Ruijven



Summary

- **MSD – high productivity while undergoing transitions, challenges**
- **93 publications in three years (2016-2018)…with ~40 in 2019…many highly cited**
- **2018 Nobel Prize awarded to PI Nordhaus** in Economic Sciences for work performed in the 1990s.
- **Substantial volume of new, open source scientific code** (e.g., *Hector, Tethys, Xanthos, Demeter, fldgen and more)*
- **Training** on new model/analysis/data platforms…e.g., GCAM training in College Park at JGCRI:
    - Scientists/modelers from nearly 20 countries
    - Energy industry…from EPRI to Exxon/Mobile
    - Interagency and intergovernmental
- Major enhancements to **web presence**…a community "work in progress"
- Expanded **teaming and collaborations** (with DOE incentives) leading to a team-of-teams approach and functional community of practice led by ***Richard Moss (PNNL/Princeton), Pat Reed (Cornell), and Erwan Monier (UC Davis)***
- Strong history of…and continued emphasis on…collaborative, interagency engagement

https://climatemodeling.science.energy.gov/program/multisector-dynamics

Questions